Renewable energies

Wind and solar power resource evaluation

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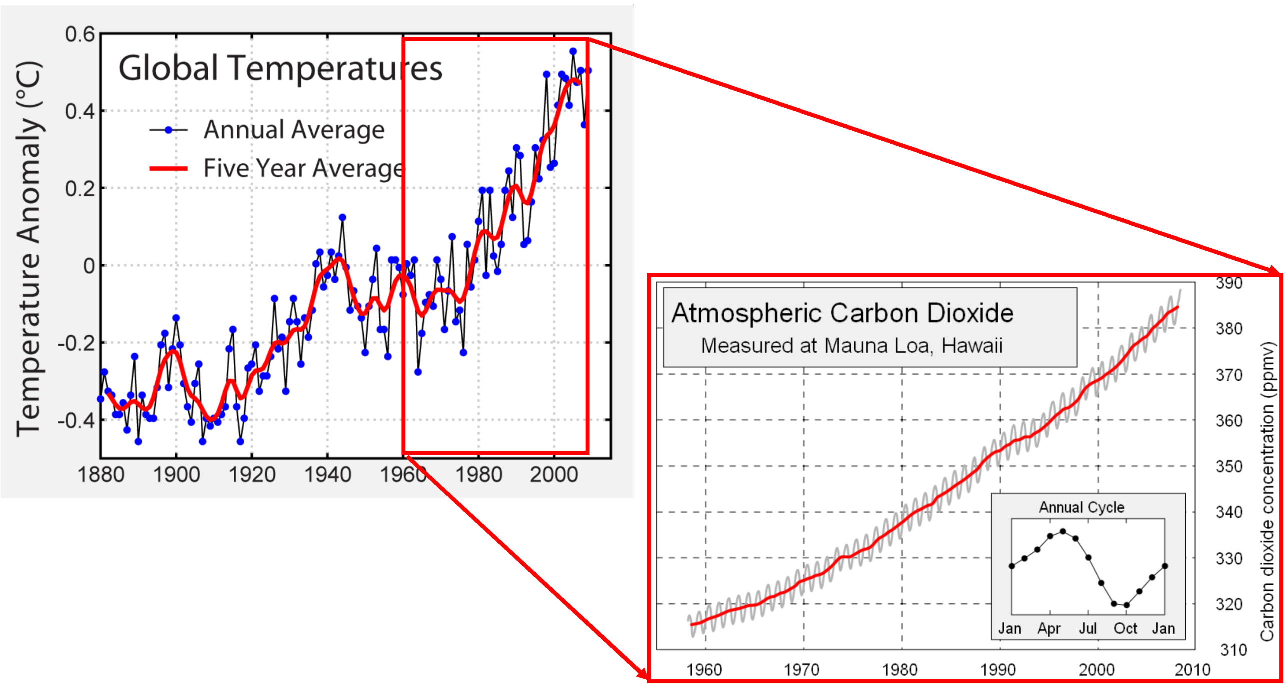
Lecture content

- Renewable wind and solar energies: the context
  - An economical and environmental necessity
  - Wind energy: an introduction
  - Solar energy : an introduction
- Basic knowledge in geophysics for energy resource evaluation
  - Earth energy budget and atmospheric motion
  - Clouds and aerosols
  - Near surface wind
- Wind and solar energy resource evaluation
  - Wind energy resources
  - Solar energy resources
  - Measurement, modeling and forecast

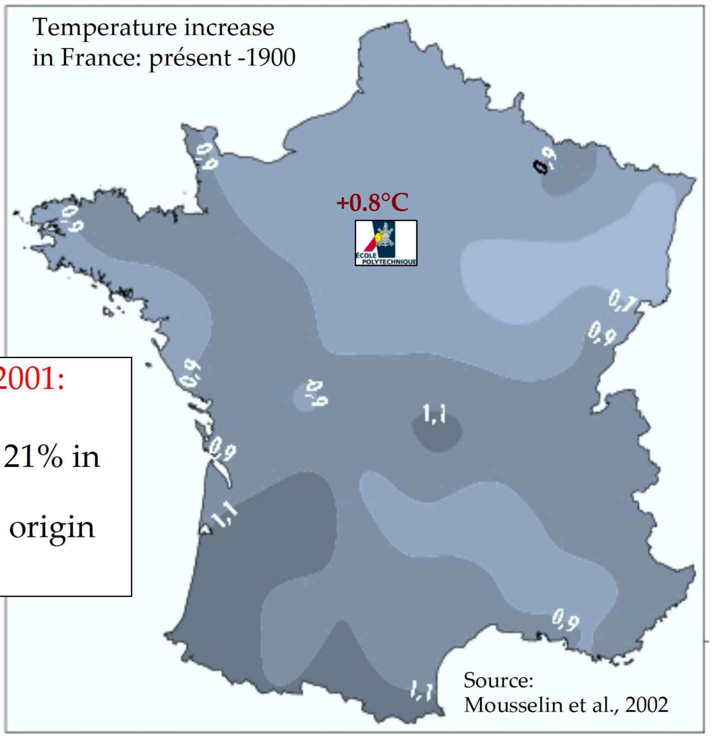
Environmental context

- Global temperature and atmospheric carbone dioxide evolution



- Consequences

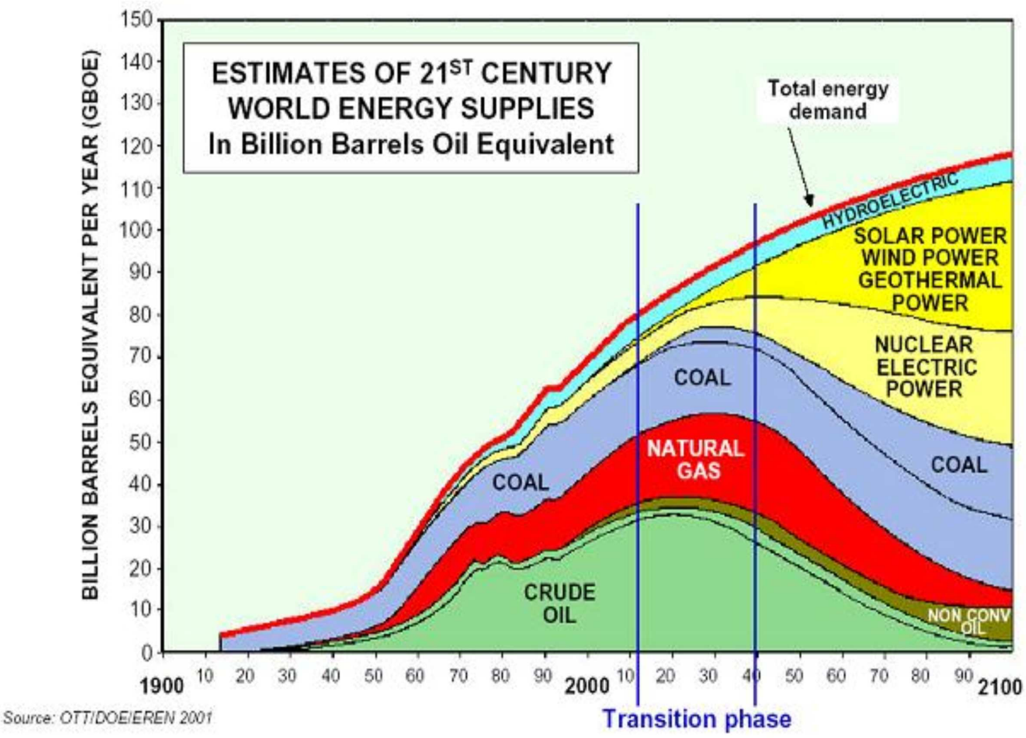
Demonstrations against global warming more and more frequent!!



European renewable energy policy in 2001:

- 5.75% of biofuels in 2010
- *Clean* electricity, from 14% in 1997 to 21% in 2010
- 50% of heat production of renewable origin in 2015

Economical and ecological necessity



- Domestic energy consumption
  - Household in temperate climate: average energy in a household a year consists of 20 MWh.

Average domestic energy consumption per household in temperate climates

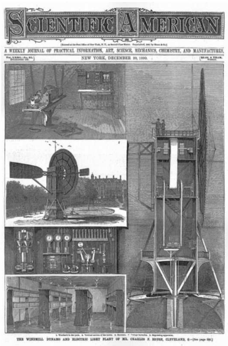
Heating	12000 kW·h/yr (1400 watts)
Hot water	3000 kW·h/yr (340 watts)
Cooling/refrigeration	1200 kW·h/yr (140 watts)
Lighting	1200 kW·h/yr (140 watts)
Washing and drying	1000 kW·h/yr (110 watts)
Cooking	1000 kW·h/yr (110 watts)
Miscellaneous electric load	600 kW·h/yr (70 watts)

- Elements of comparison
  - Windmill: from few kW to 6 MW ; most windmills in France produce 1 - 3 MW).
  - Photovoltaïc solar plant: from few hundreds W to 20 MW (record 20 MW at Beneixama in Spain)
  - Thermodynamical solar plant: from 2 to 350 MW (record: 354 MW at Luz Solar Energy plant in the Mojave desert in California, USA)
  - Hydro-electrical plant: few kW to 3 000 MW (record : 32 700-MW turbines, i.e. 22 400 MW at the 3 groges dam in China)
  - Nuclear plant: from about 900 to 1 300 MW (record : 1 550 MW at Civaux, south of Poitiers).

Short history

- Windmills





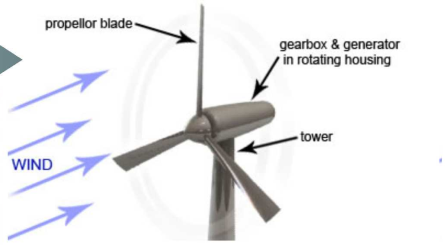

Antiquity — 1100 — 1887 — 1957

Antiquity	1100	1887		1957
Windmills used as a grinding mill	In Europe, first windmills used as wind pumps.	Charles F. Brush (USA) builds first windturbine producing electricity.	Poul la Cour develops several experimental windmills and conduct research in wind tunnels.	Johannes Juul buids the Gedser windturbine, precursor of the modern windmills.

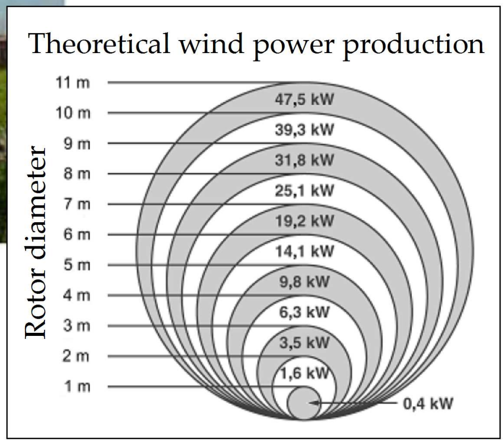
First half of XXth century, windmills confronted to tough competition with fossil fuel power plants and the national electricity network. Because of the lack of coal and petroleum during the world wars, wind power production remains used.

Horizontal-axis wind turbines (HAWT)

Large windturbine → Small windturbine



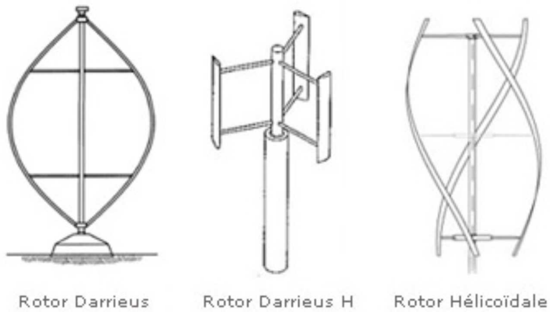
Rotation speed: 10 to 25 per minute → production ~**2MW** (~electricty for 2000 homes, except heating).

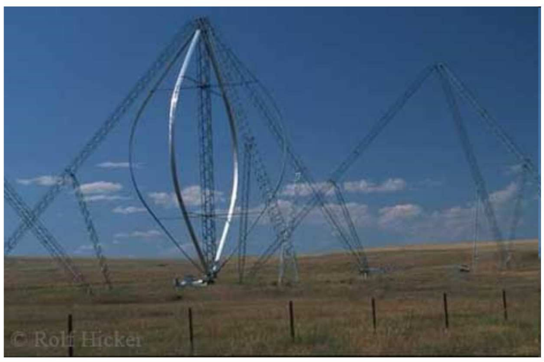


Vertical-axis wind turbines (VAWT)

The main rotor shaft is arranged vertically:
→does not need to be pointed into the wind to be effective (advantage on sites with highly variable wind direction).
→generator and gearbox placed near the ground (more accessible for maintenance).

Drawbacks are that some designs produce pulsating torque.





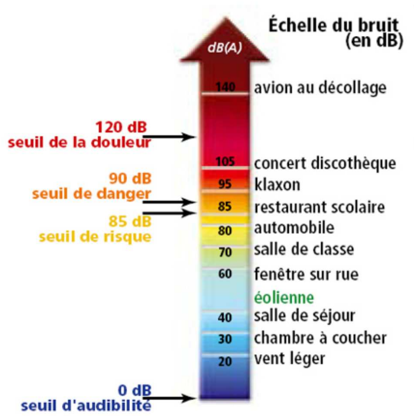
Windmill regulation and production

- Windmill regulation → extremely variable: definition of winmill zones, wind energy price, constraints (environmental protection,…).
- Windwill production within the national electricty network
  - When the turbine produces more power than house needs, the extra electricity is sold to the local utility (EDF in France). The electricty price is set by the local utility.
  - Capacity factor: one element in measuring **the productivity of a wind turbine**. It compares the plant's actual production over a given period of time with the amount of power the plant would have produced if it had run at full capacity for the same amount of time.

$$\text{Capacity Factor} = \frac{\text{Actual amount of power produced over time}}{\text{Power that would have been produced if turbine operated at maximum output 100\% of the time}}$$

  A wind plant is "fueled" by the wind, which blows steadily at times and not at all at other times. Although modern utility-scale wind turbines typically operate 65% to 90% of the time, they often run at less than full capacity. Therefore, a capacity factor of 25% to 40% is common, although they may achieve higher capacity factors during windy weeks or months.
- Major concerns: … the Don Quixotte fight continues

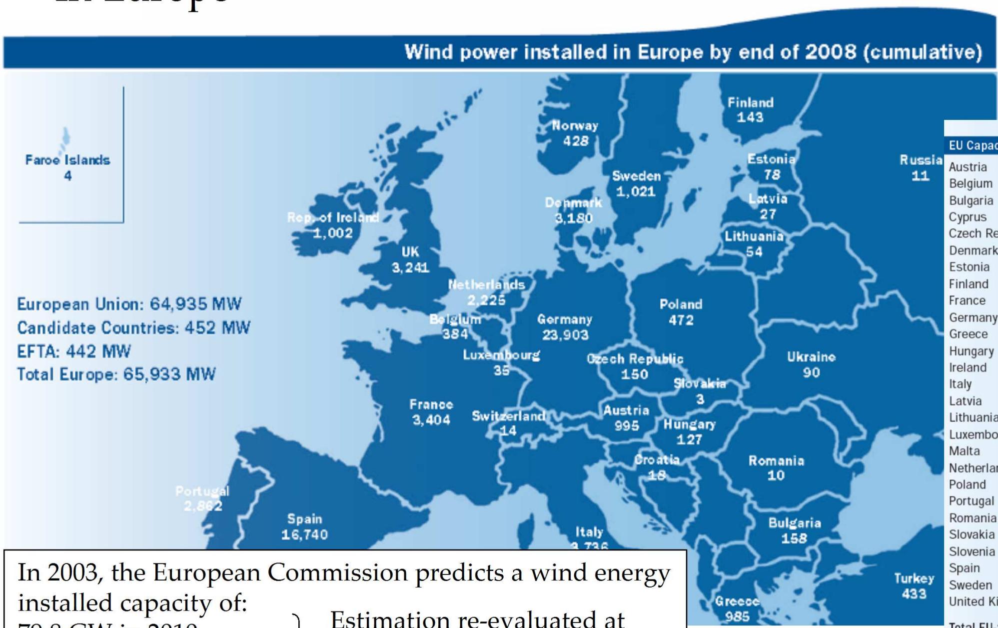
- Major concerns
  - "Bird guillotine" killing birds.
  - Constant noise.
  - Property values lowering.
  - Ruin of the character of the neighborhood.
  - …



The Don Quixotte fight continues!!

Wind energy power around the world

- In Europe

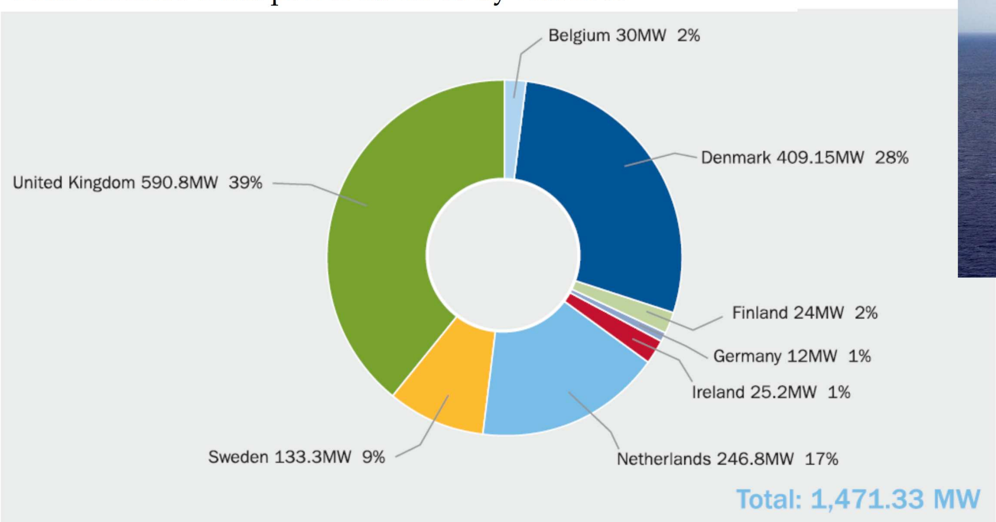


EU Capacity (MW)	End 2007	Installed 2008	End 2008
Austria	982	14	995
Belgium	287	104	384
Bulgaria	57	101	158
Cyprus	0	0	0
Czech Republic	116	34	150
Denmark	3,125	77	3,180
Estonia	59	20	78
Finland	110	33	143
France	2,454	950	3,404
Germany	22,247	1,665	23,903
Greece	871	114	985
Hungary	65	62	127
Ireland	795	208	1,002
Italy	2,726	1,010	3,736
Latvia	27	0	27
Lithuania	51	3	54
Luxembourg	35	0	35
Malta	0	0	0
Netherlands	1,747	500	2,225
Poland	276	196	472
Portugal	2,150	712	2,862
Romania	8	2	10
Slovakia	5	0	3
Slovenia	0	0	0
Spain	15,131	1,609	16,740
Sweden	788	236	1,021
United Kingdom	2,406	836	3,241
Total EU-15	55,854	8,067	63,857
Total EU-12	663	417	1,078
Total EU-27	56,517	8,484	64,935
Of which offshore and near shore	1,114	357	1,471

In 2003, the European Commission predicts a wind energy installed capacity of:
79.8 GW in 2010
144.8 GW in 2020
213.5 GW in 2030

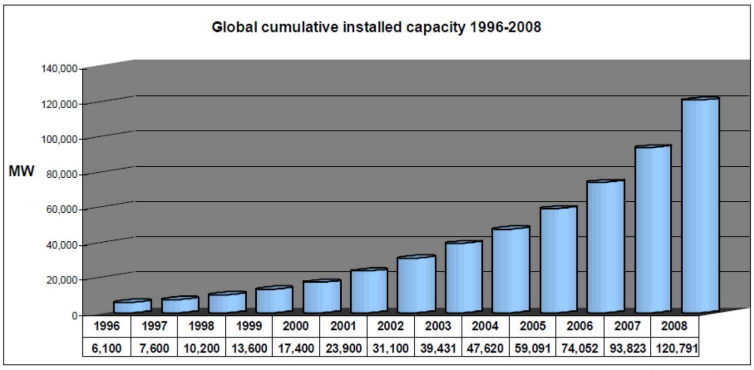
Estimation re-evaluated at higher level 9 times between 1996 and 2003!!

Offshore wind energy power in Europe:
Total offshore wind power installed by end 2008

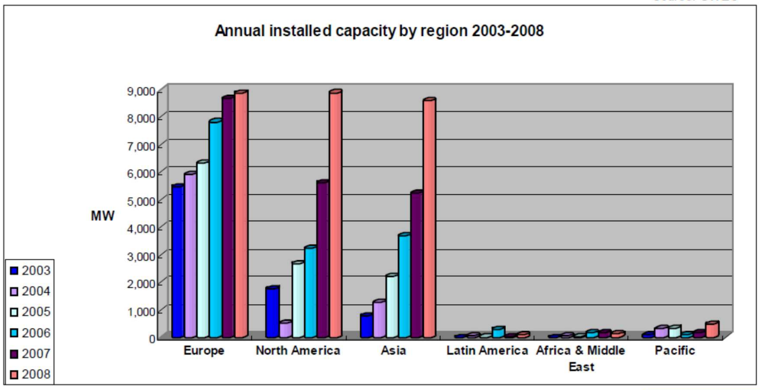


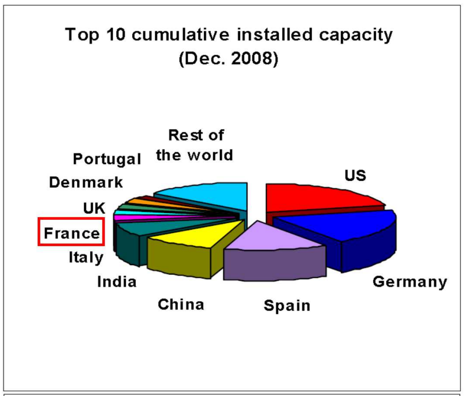
Source: EWEA

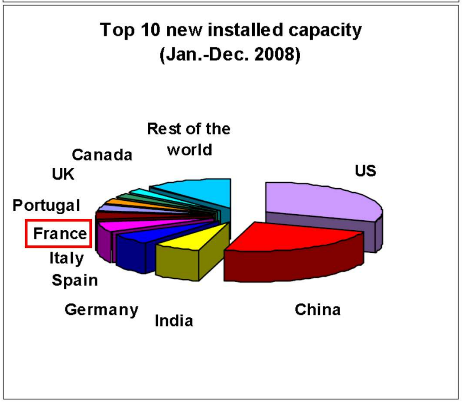
- World wind energy power



Source: GWEC







Source: GWEC

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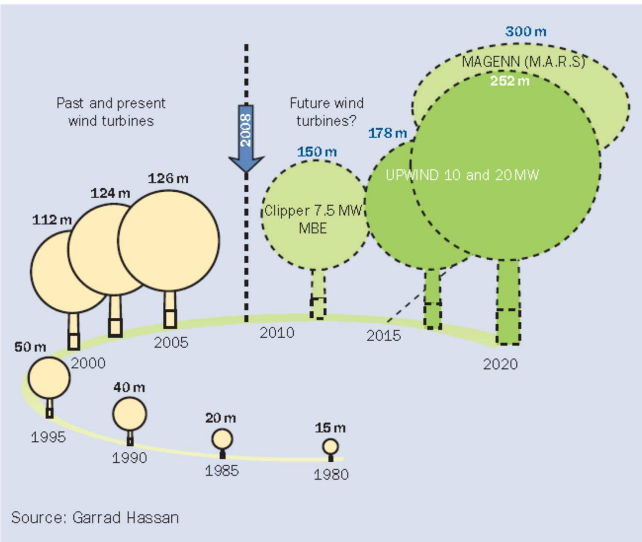
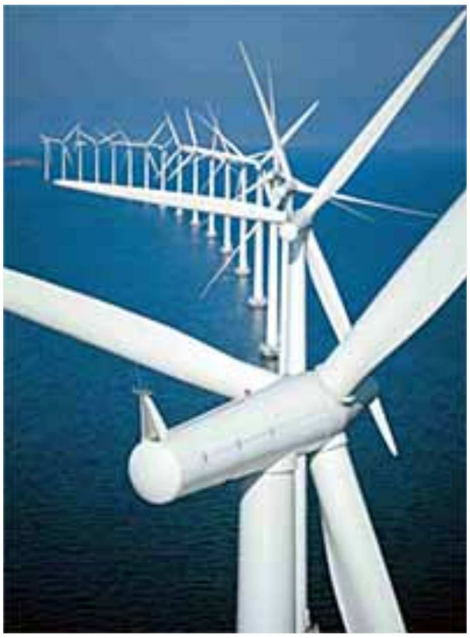
Solar energy: an introduction

Wind energy production challenges

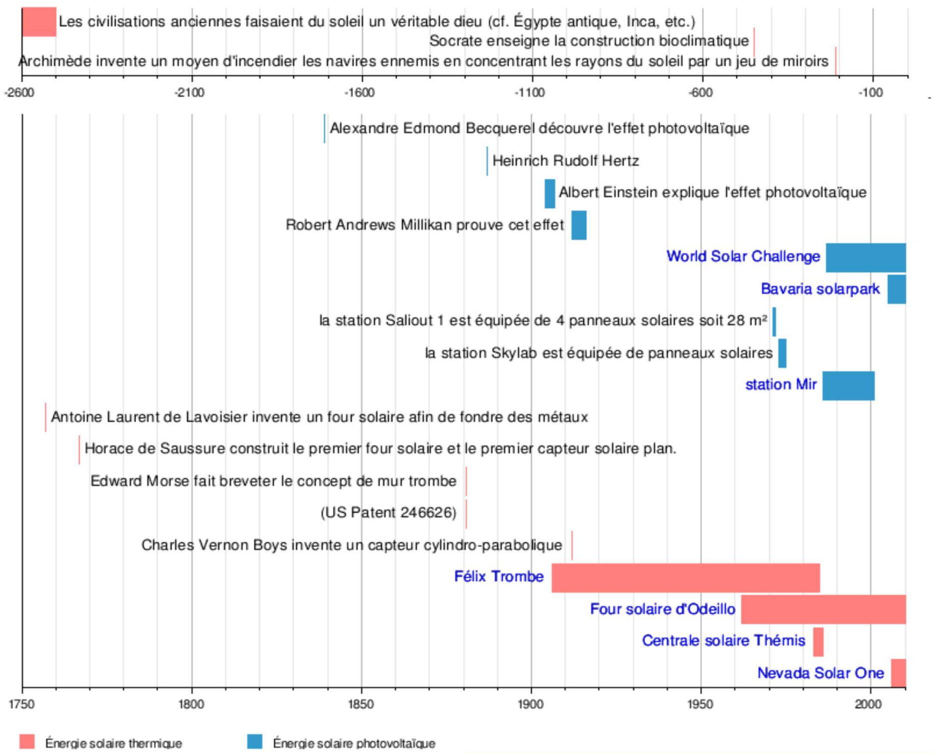
- Windmill size



- Offshore wind energy production
- Windturbine farms



Short history



Several techniques

Techniques to directly receive a portion of this energy are available and are constantly improved. We can distinguish passive solar, solar photovoltaic and solar thermal


Automatic laundry service operated with solar energy.

- **Passive solar:** The oldest and most important use of solar energy is to receive the direct input of solar radiation. In passive solar building, one must take account of energy during solar building design. The thermal insulation is important to optimize the proportion of passive solar gain in heating and lighting of a building. The passive solar gain can make significant energy savings.

- **Solar photovoltaic:** Solar photovoltaic electricity is produced by processing a portion of solar radiation with a photocell. Several cells are connected together on a solar module. Several modules are combined to form a solar system. The solar system can provide power on site (in association with a storage medium) or inject it, after transformation into alternating current, in an electrical distribution system (storage, then not being required). This energy is now quantitatively negligible while, with or without a network, it can durably meet the energy needs of a house (sensors on the roof) or industry, unlike other forms of solar energy that produces only heat, without maintenance.

- **Solar thermal:** Solar thermal power is to use heat from solar radiation. This radiation comes in different ways:
  - used for direct heat: hot water heaters and solar heaters, solar cookers and dryers;
  - used indirect heat for another purpose: thermodynamic solar plants.

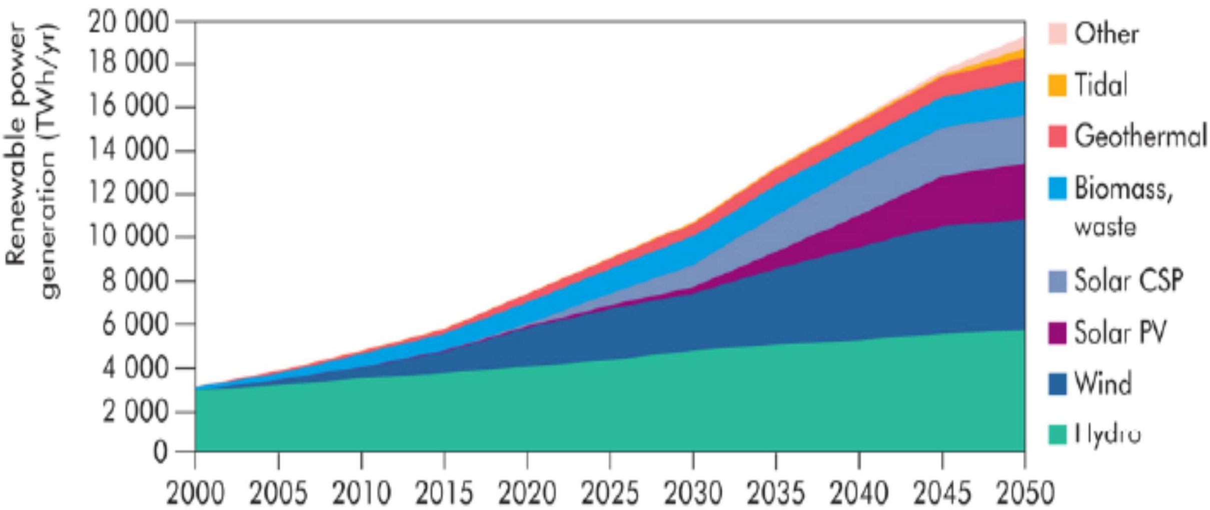
  The solar thermal is a solar technology that uses solar heat to produce electricity, the same principle as a traditional power plant (generating high pressure steam which is then turbines), or possibly direct mechanical work (the term solar mechanics is then used).

Power engine in Font Romeu France

Solar plant in California (Kramer Junction)

Solar energy power in the world

Renewable energy development: Scenario Blue Map (AIE)



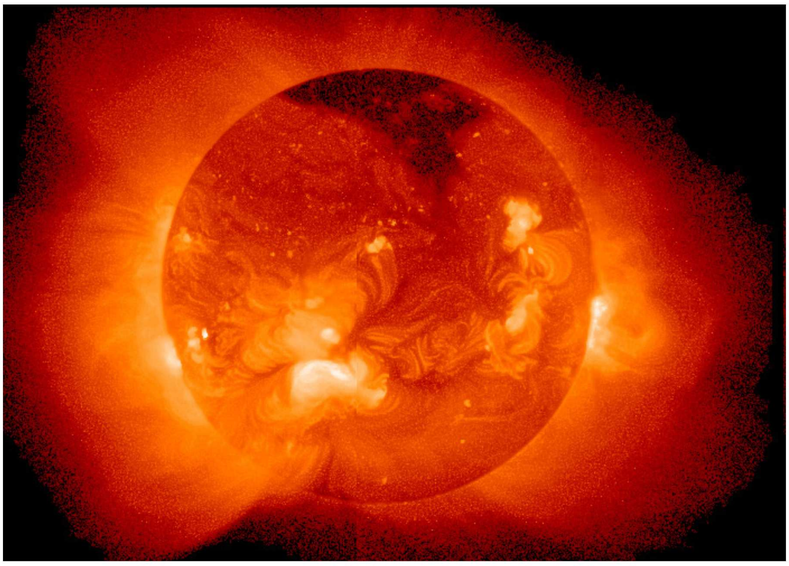
Source : *Energy Technology Perspective 2008, AIE - Synthèse disponible sur : http://www.iea.org*

Solar therman (CSP) and photovoltaic (PV) electricityin 2050 :

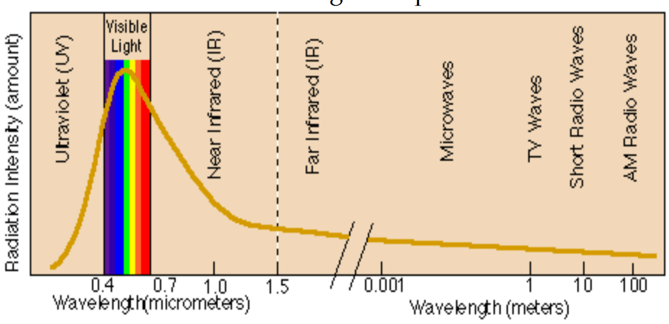
- ~2500 TWh production per year each
- ~13 % of worldwide renewable energy production each

The Sun: the Earth's source of energy

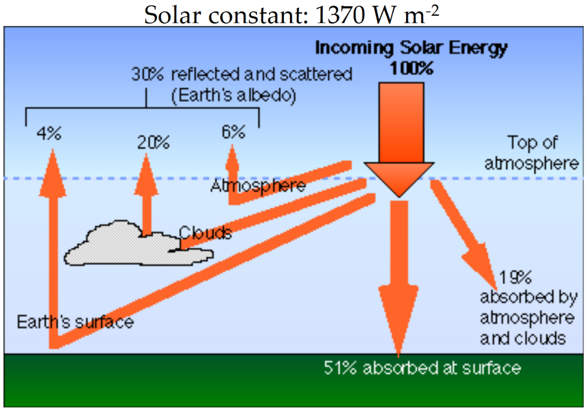
- Per year, the Earth recieves from the Sun 8380 times the total worldwide energy consumption (11 milliards de tep). France recieves from the Sun 200 times its annual energy consumption (250 Mtep)



Solar electromagnetic spectrum

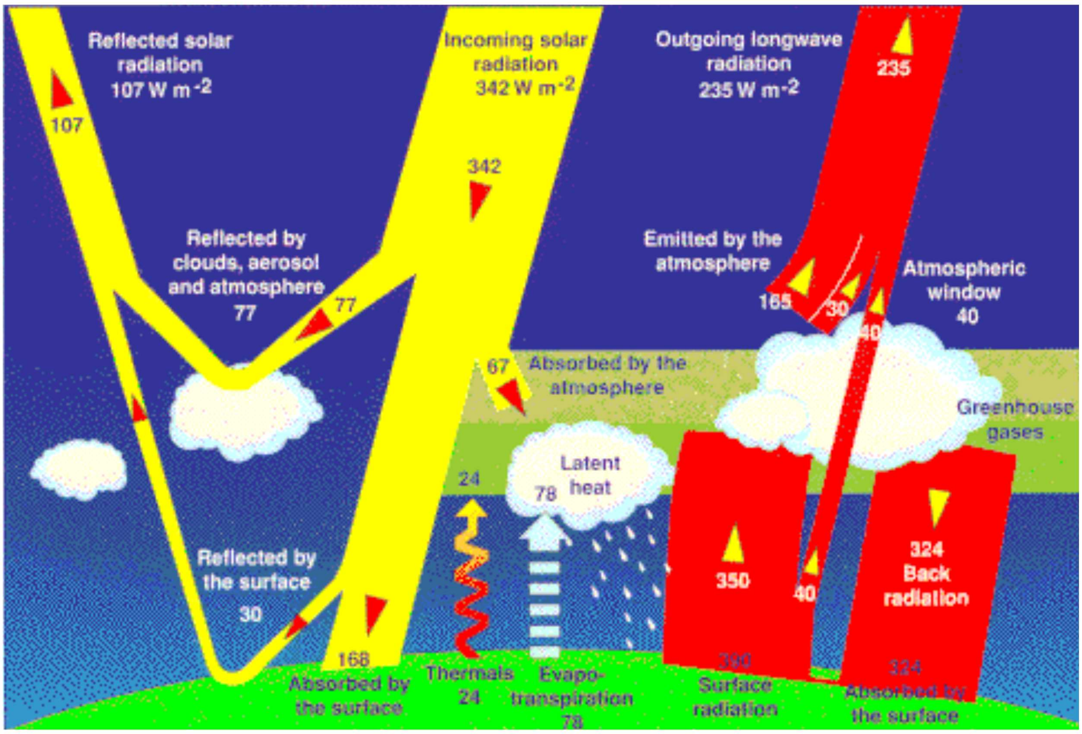


Solar constant: 1370 W m^{-2}



Surface	Albédo (%)	Surface	Albédo (%)
Snow	80-95	Dark surface	5-15
Ice	30-40	Turf	10-30
Thick cloud	60-90	Forest	5-15
Thin cloud	30-50	Water	10
Moist sand	20-30	Dry sand	35-45
Cement	15-25	Asphalt	5-10

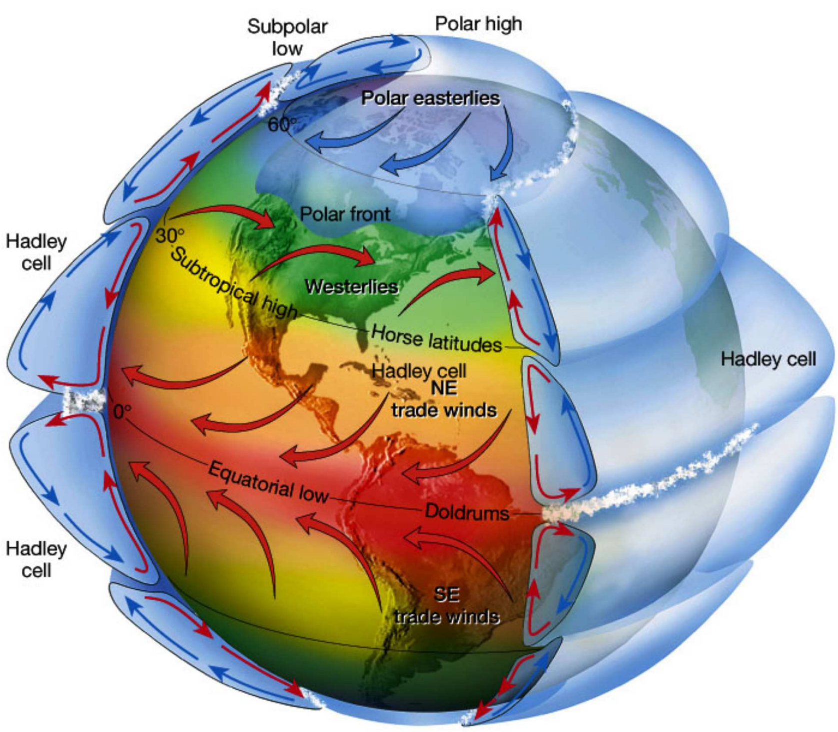
Earth energy budget



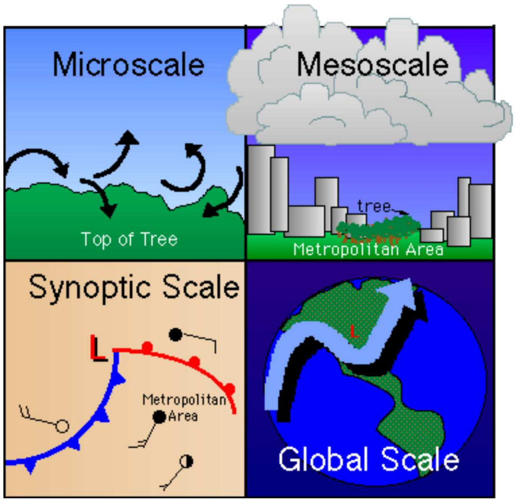
Global atmospheric circulation

- The Sun heats the equatorial regions much more than the polar regions. In response to this, three cells develop.

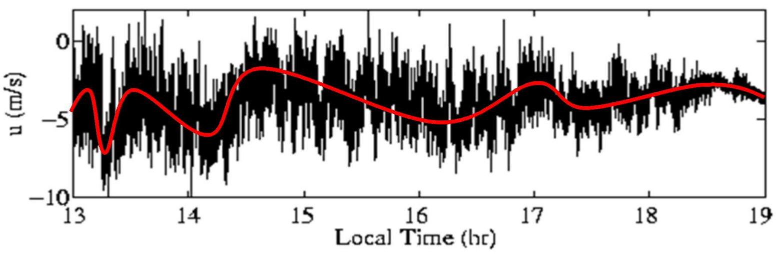
- The Earth rotates so air traveling southward from the north pole will be deflected to the right. Air traveling northward from the south pole will be deflected to the left.



Multi-scale wind variability



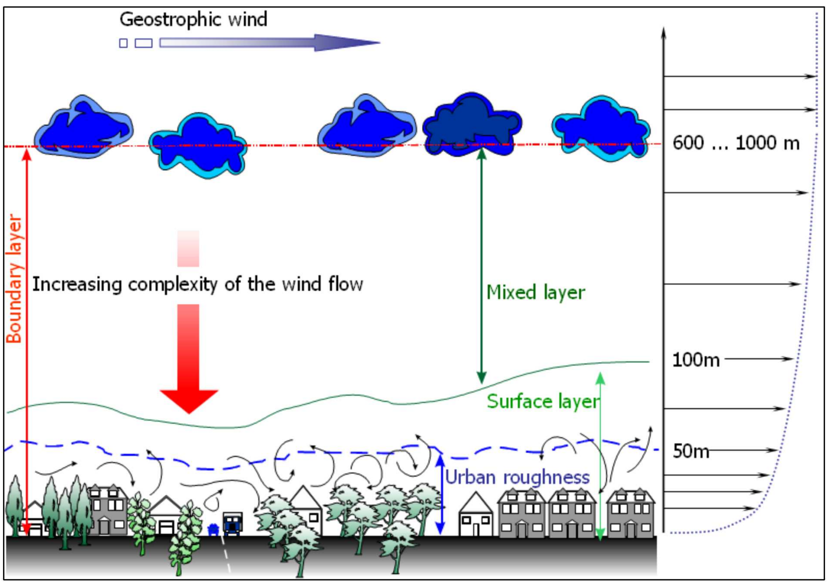
Scale separation ($q = \overline{q} + q'$)



Equations for the wind

$$\underbrace{\frac{d\overline{U}_i}{dt}}_{\text{Evolution}} = \underbrace{-\frac{1}{\overline{\rho}}\frac{\partial \overline{p}}{\partial x_i}}_{\text{Pressure gradient}} + \underbrace{f_c\,\varepsilon_{ij3}\overline{U}_j}_{\text{Coriolis force (Earth rotation)}} - \underbrace{\frac{\partial\left(\overline{u_j' u_i'}\right)}{\partial x_j}}_{\text{Turbulence}}$$

Vertical structure of the wind



Free troposphere: geostrophic wind

Turbulence: negligible

Boundary layer

Mixed layer

All terms of same order of magnitude

Surface layer

Pressure gradient and Coriolis force negligible

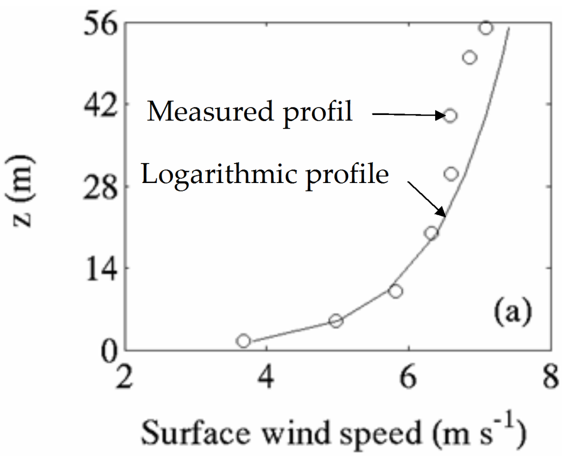
- Logarithmic law profile

Pressure gradient and Coriolis force negligible

$$\Rightarrow \overline{U}(z) = \frac{u_*}{K}\ln\left(\frac{z}{z_0}\right)$$

Logarithmic profile of the horizontal wind speed

Roughness length z_0 : Whilst it is not a physical length, it can be considered as a length-scale a representation of the roughness of the surface.



Drobinski et al. (2007)

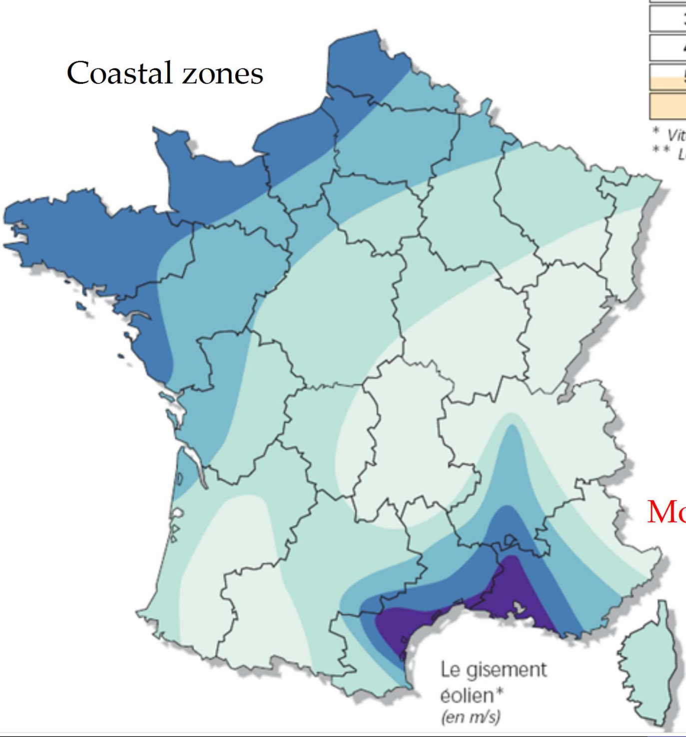
Thermal stratification

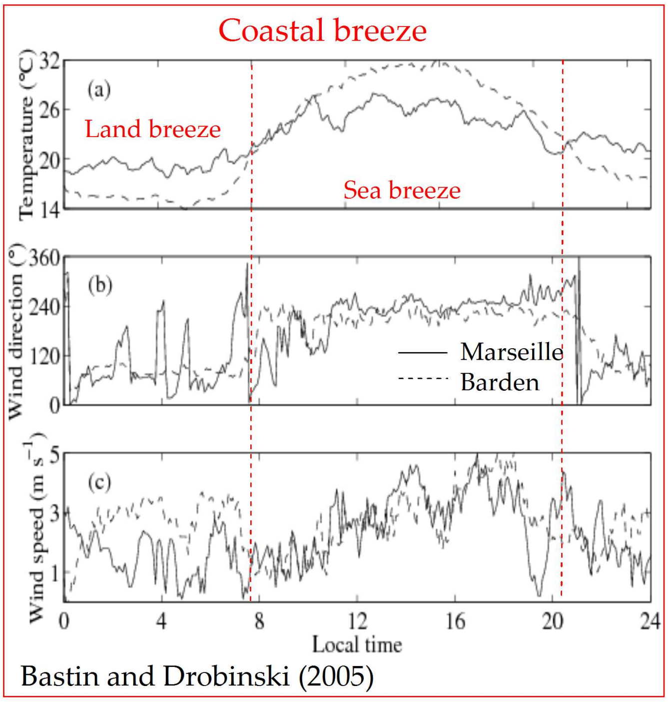
$$\overline{U}(z) = \frac{u_*}{K}\left[\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right)\right]$$

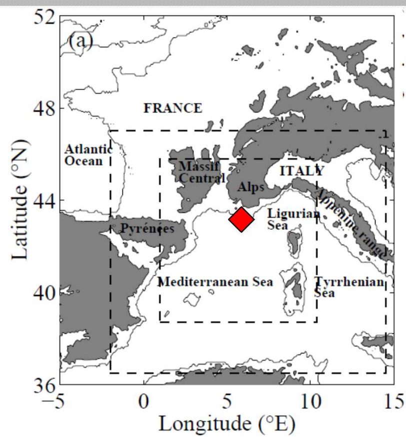
Type of surface	z_0 (m)
Ice	10^{-5}
Steady ocean	10^{-4}-10^{-3}
Snow	2×10^{-3}
Trees, fields, …	2×10^{-2}-10^{-1}
Dense forests, small towns	10^{-1}-6×10^{-1}
Large towns	6×10^{-1}-2
Mountains	2-100

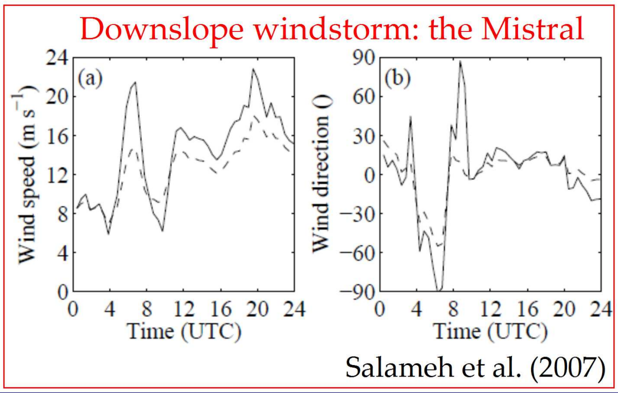
Bocage dense, bois, banlieue	Rase campagne, obstacles épars	Prairies plates, quelques buissons	Lacs, mer	Crêtes**, collines	
<3,5	<4,5	<5,0	<5,5	<7,0	Zone 1
3,5 - 4,5	4,5 - 5,5	5,0 - 6,0	5,5 - 7,0	7,0 - 8,5	Zone 2
4,5 - 5,0	5,5 - 6,5	6,0 - 7,0	7,0 - 8,0	8,5 - 10,0	Zone 3
5,0 - 6,0	6,5 - 7,5	7,0 - 8,5	8,0 - 9,0	10,0 - 11,5	Zone 4
>6,0	>7,5	>8,5	>9,0	>11,5	Zone 5

* Vitesse du vent à 50 mètres au-dessus du sol en fonction de la topographie
** Les zones montagneuses nécessitent une étude de gisement spécifique









Clouds

Cloud classification

High level clouds (~ 10 km)


Cirrus


Cirrocumulus


Cirrostratus


Contrail

Medium level clouds (~ 2-5 km)


Altostratus


Altocumulus

Low level clouds (< 2 km)


Stratocumulus


Stratus


Cumulus

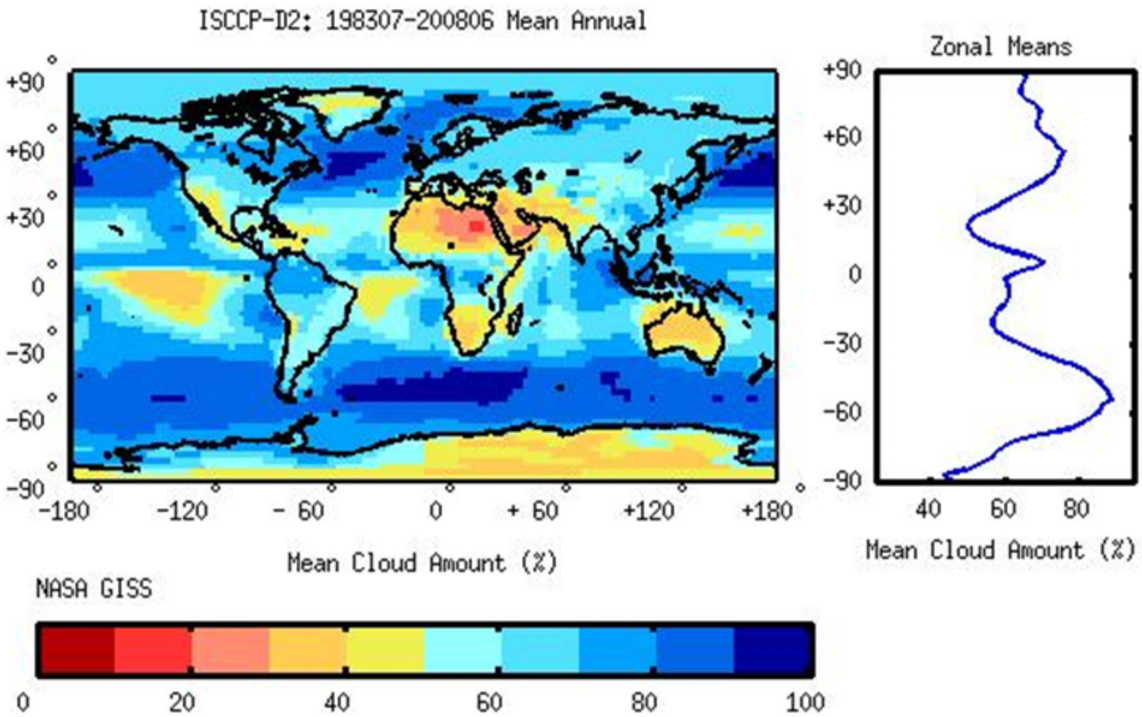
z

« Vertical » clouds


Cumulonimbus

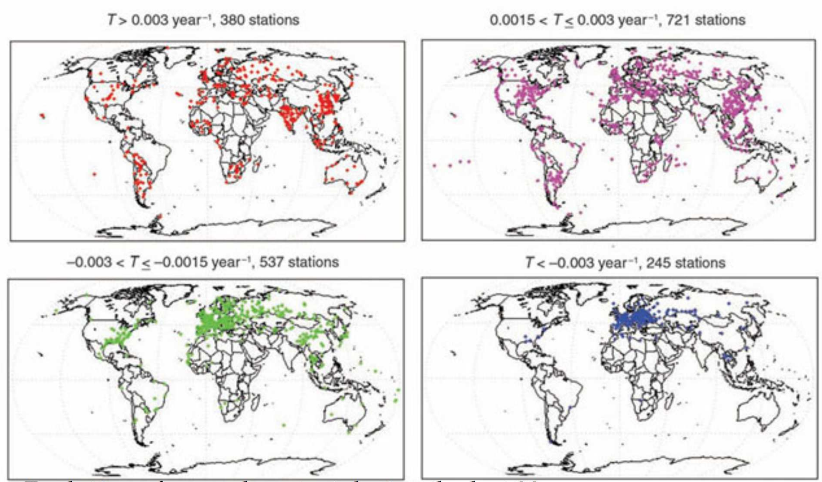

Nimbostratus

- Cloud cover



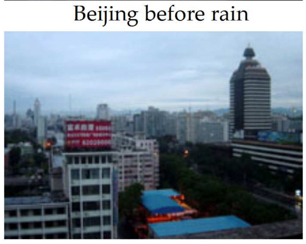
Aerosols

- Distribution, evolution and visibility



Evolution of aerosol content during the last 30 years

Beijing before rain



Beijing after rain

… not only in Beijing, in Paris too!!

Optical depth

Optical depth, or optical thickness is a measure of transparency. The optical depth is a measure of the proportion of radiation absorbed or scattered through a partially transparent medium. If I_0 is the intensity of radiation at the source and I is the observed intensity after a given path, then optical depth τ is defined by the following equation:

$$I/I_0 = e^{-\tau}$$

- When τ is small: little attenuation
- When τ is large: strong attenuation

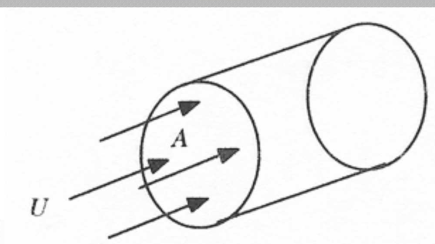
Aerosols	$\tau<1$
Ice clouds (cirrus): thin clouds	$1<\tau<3$
Water clouds: thick clouds	$3<\tau<80$

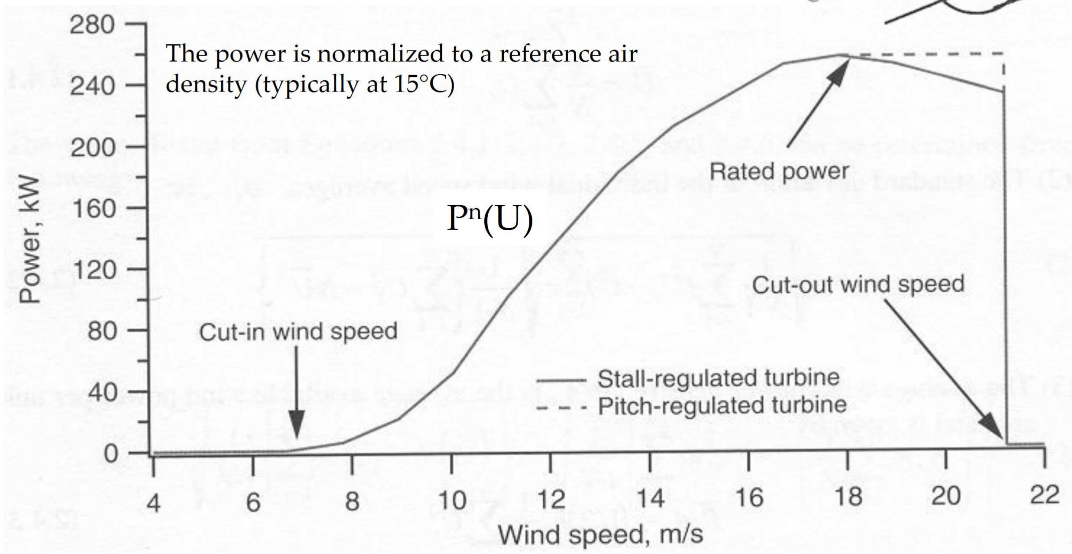
Clouds and aerosols are the largest sources of solar radiation diffusion and absorption and they determine at one location the available solar power.

Available wind power

Power curve

$$P^n = \frac{1}{2}\rho U^3 A$$ (kinetic energy per unit of time through surface A)





Coefficient of power

- The total energy available in the wind through a surface A is:

$$P^n = (1/2)\rho A U^3$$

- Wind turbines extract energy by slowing down the wind (it however cannot extract the total energy available in the wind otherwise it would need to stop 100% of the wind; see Betz law). The energy produced by the wind turbine is thus:

$$P^n_w = (1/2)C_p \rho A U^3$$

- The coefficient of power of a wind turbine C_p is thus a measurement of how efficiently the wind turbine converts the energy in the wind into electricity

$$C_p = \frac{P^n_w}{P^n} = \frac{\text{Energy produced by wind turbine}}{\text{Total energy available in the wind}}$$

Statistical wind distribution

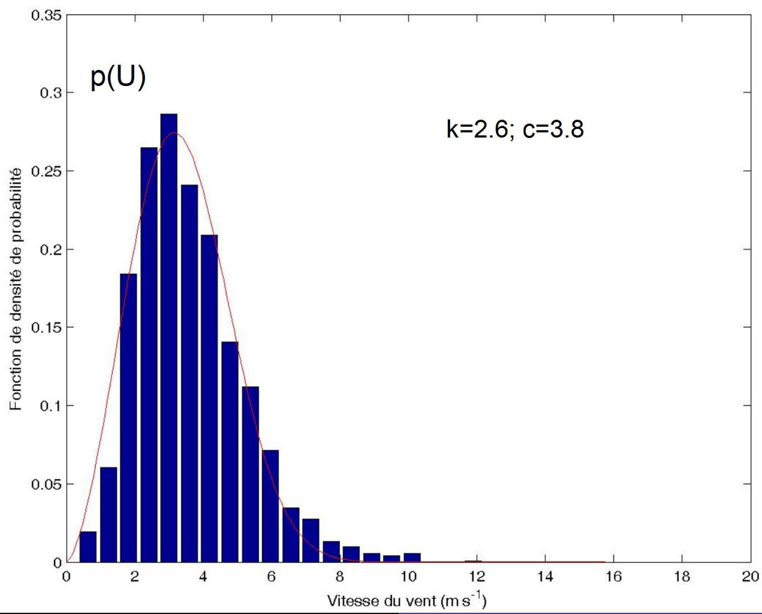
- Energy pattern

$$K_e = \overline{U^3} / \overline{U}^3$$

- Wind power produced by wind turbine

$$\overline{P_w} = (1/2)\overline{\rho} A C_P \overline{U}^3 K_e$$

(C_p is constant)

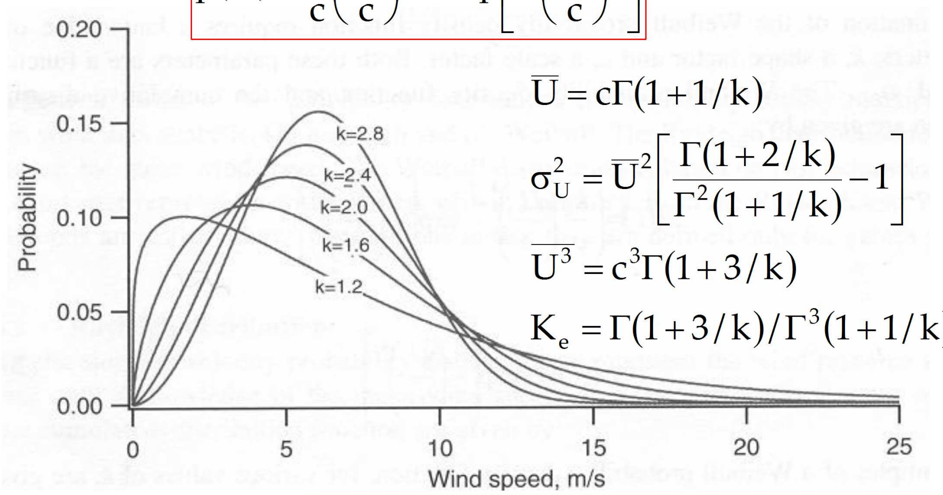


Weibull distribution

In probability theory and statistics, the **Weibull distribution** is a continuous probability distribution. It is named after Waloddi Weibull who described it in detail in 1951, although it was first identified by Fréchet (1927) and first applied by Rosin & Rammler (1933) to describe the size distribution of particles.

$$p(U)=\frac{k}{c}\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

The Weibull distribution is used to describe wind speed distributions, as the natural distribution often matches the Weibull shape



$$\overline{U}=c\Gamma(1+1/k)$$

$$\sigma_U^2=\overline{U}^2\left[\frac{\Gamma(1+2/k)}{\Gamma^2(1+1/k)}-1\right]$$

$$\overline{U^3}=c^3\Gamma(1+3/k)$$

$$K_e=\Gamma(1+3/k)/\Gamma^3(1+1/k)$$

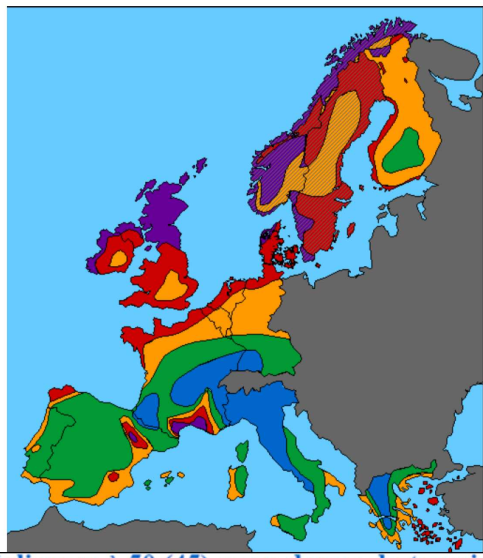
Class of wind energy

Classes of Wind Power Density at 10 m and 50 m(a)

	10 m (33 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Speed(b) m/s (mph)	Wind Power Density (W/m^2)	Speed(b) m/s (mph)
1	<100	<4.4 (9.8)	<200	<5.6 (12.5)
2	100 - 150	4.4 (9.8)/5.1 (11.5)	200 - 300	5.6 (12.5)/6.4 (14.3)
3	150 - 200	5.1 (11.5)/5.6 (12.5)	300 - 400	6.4 (14.3)/7.0 (15.7)
4	200 - 250	5.6 (12.5)/6.0 (13.4)	400 - 500	7.0 (15.7)/7.5 (16.8)
5	250 - 300	6.0 (13.4)/6.4 (14.3)	500 - 600	7.5 (16.8)/8.0 (17.9)
6	300 - 400	6.4 (14.3)/7.0 (15.7)	600 - 800	8.0 (17.9)/8.8 (19.7)
7	>400	>7.0 (15.7)	>800	>8.8 (19.7)

(a) Vertical extrapolation of wind speed based on the 1/7 power law

(b) Mean wind speed is based on the Rayleigh speed distribution of equivalent wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) of elevation.
(from the Battelle Wind Energy Resource Atlas)

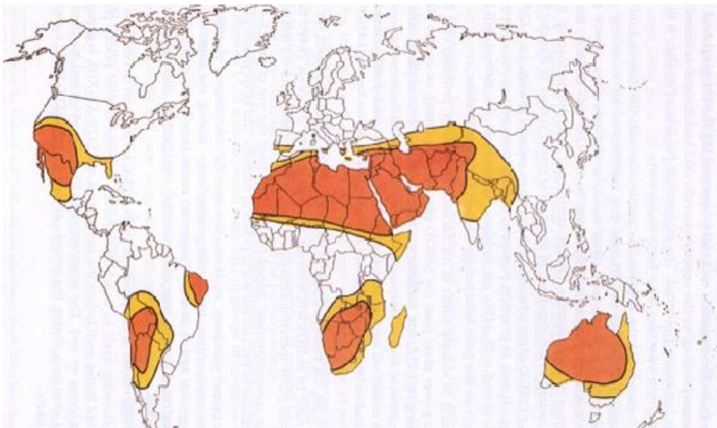


Ressources éoliennes à 50 (45) m au-dessus du terrain

Couleur	Terrains avec obstacles		Terrains dégagés		Au bord de la mer		Mer ouverte		Collines et crêtes de colline	
	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2
(violet)	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
(rouge)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(orange)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(vert)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
(bleu)	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

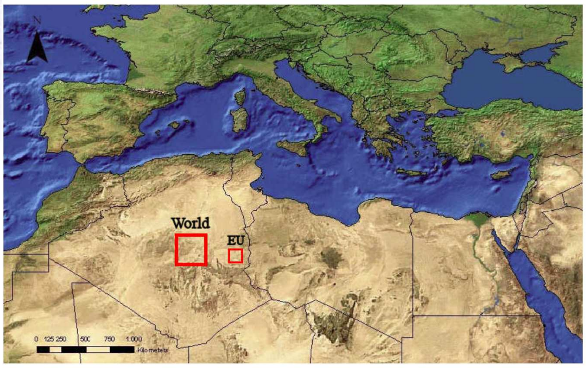
Batelle class

Illimited resources but... localized

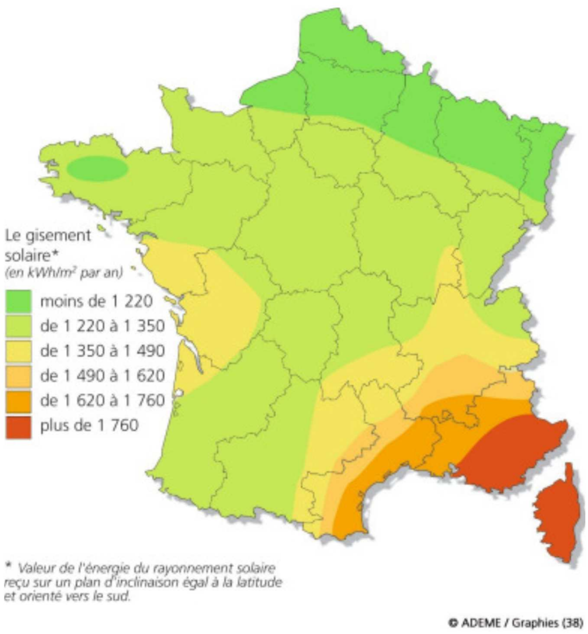


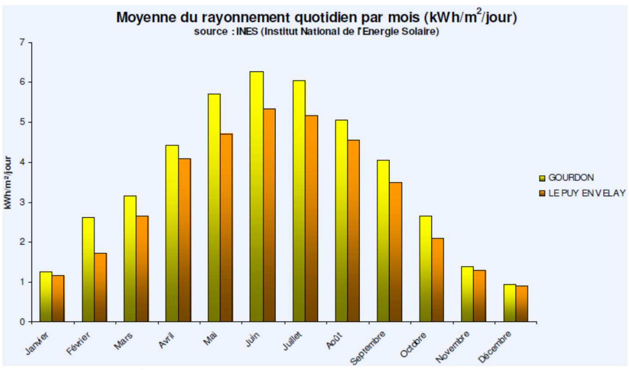
Source: C. Philibert (1991)

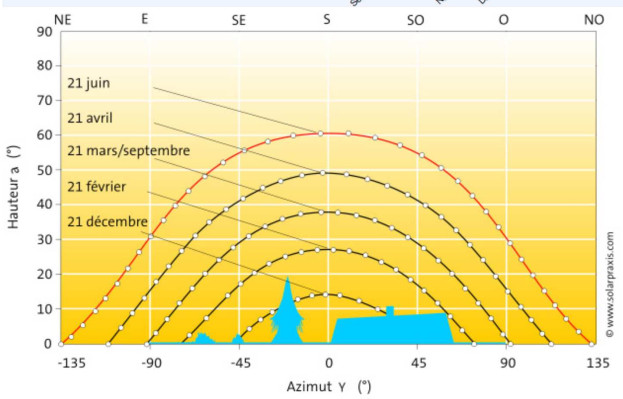
1% of the arid and semi-arides area is enough to produce the electricity annually used worlwide



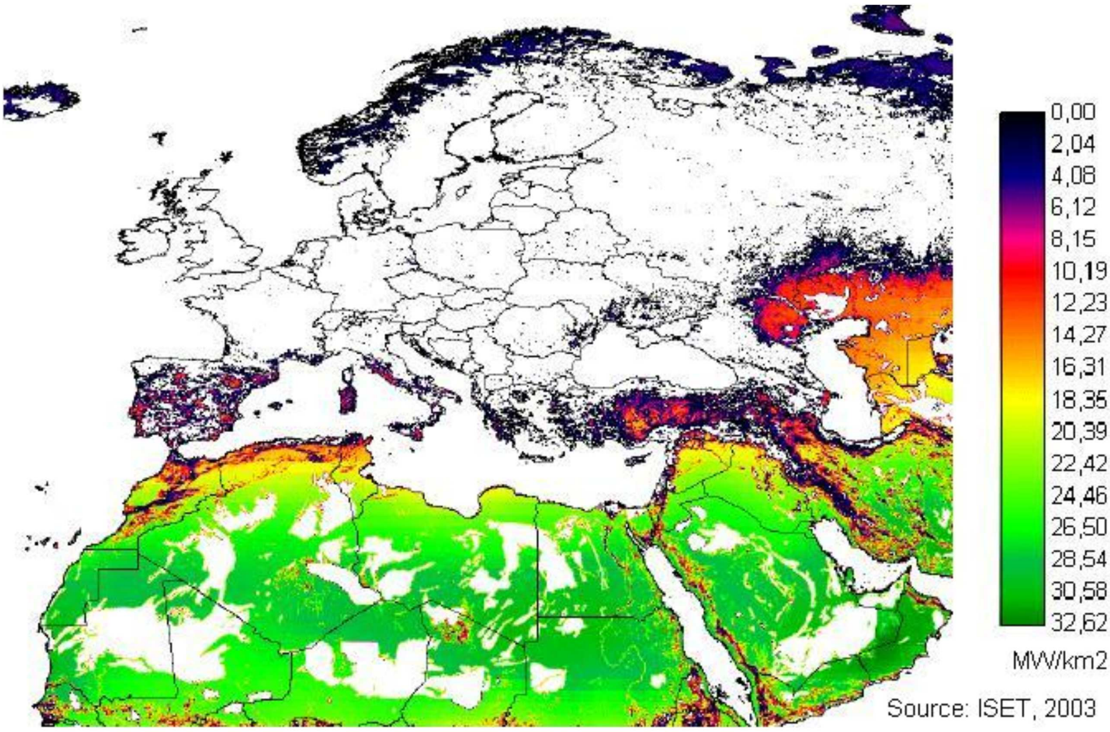
Avaliable solar energy







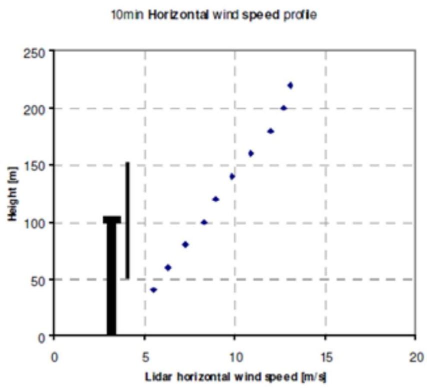
Production potential in the Mediterranean basin



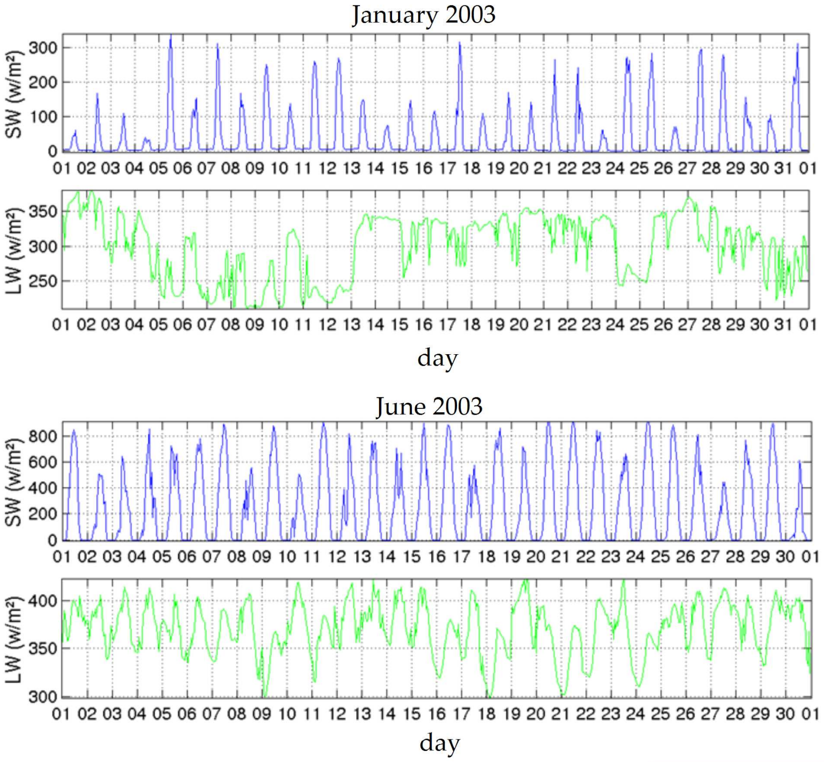
Wind measurement

Types of sensors

- In-situ sensors
  - Measures made at the sensor location
  - Drawbacks: modification of the flow by the sensor; low representativness of the measurement
  - Advantages: high sensitivity and accuracy, fast sampling, simplicity, …
- Remote sensors
  - Measurements of acoustic or electromagnetic fields generated or modified by the atmosphere away the sensor
  - Drawbacks: size, cost, complexity, low signal to noise ratio, low spatial and temporal resolution, …
  - Advantages: volumic and temporal description of the atmosphere (high representativeness)



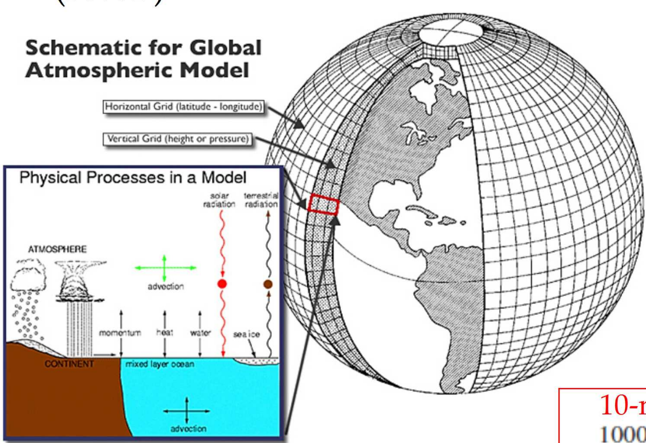
Radiation measurement



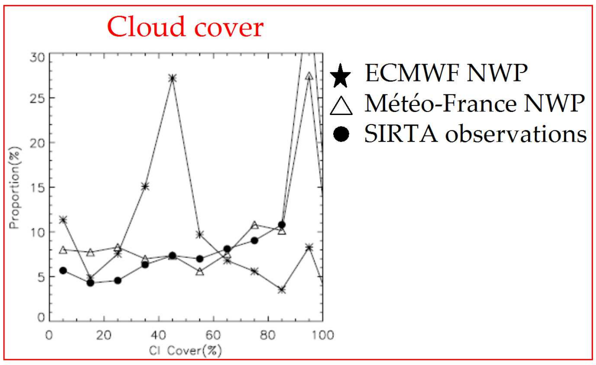
Pyrgeometer and pyranometer at SIRTA observatory

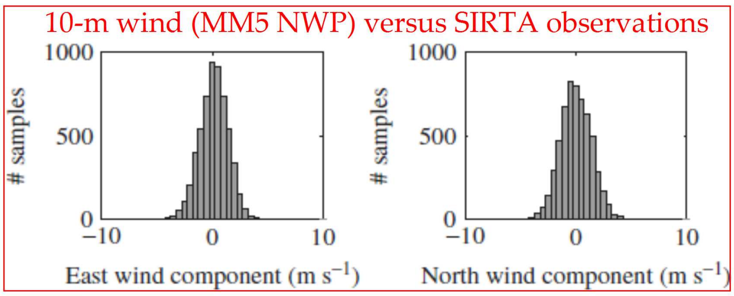
Modeling and forecast

- Numerical weather prediction (NWP)

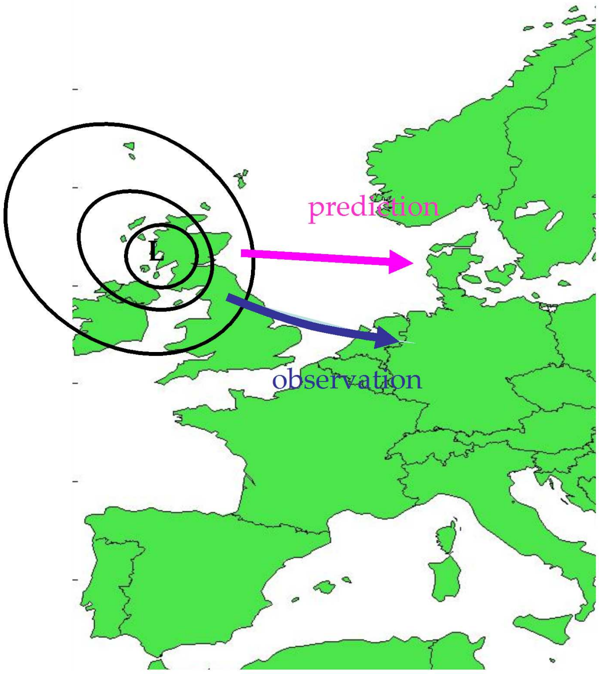


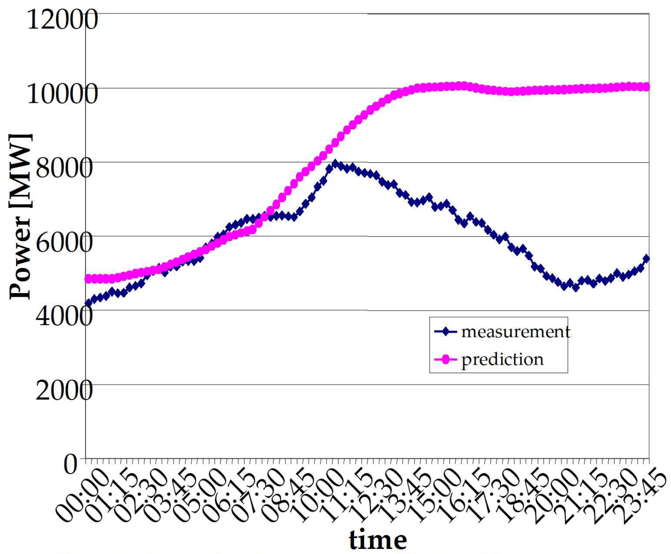
- Skill scores





- Example of impact of forecast uncertainty on energy production estimate





Predictions for Germany : Path of low-pressure system was different than predicted, maximum error: 5500 MW, could have been avoided by extreme event correction.

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  - Canadian atlas: Benoît, R. (www.atlaseolien.ca)
  - US atlas: Elliot, D.L. et al. (1989) Wind Energy Resource Atlas of the United States, PNL report DOE/CH10094-4. (www.nrel.gov/wind/pubs/atlas)
  - European atlas: Troen, I., Petersen, E.L. (1989) European Wind Atlas, RISO National Laboratory, Danemark

<u>Data available on the web</u>
  - US wind maps: www.nrel.gov/wind/wind_map.html
  - Quebec wind maps: www.eole.org/carte_des_vents.htm
  - Worldwide meteorological data: RETScreen software (http://retscreen.gc.ca)
  - NASA satellite measurements: RETScreen software (http://retscreen.gc.ca)
  - High frequency data base: www.winddata.com

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  - « Les centrales solaires à concentration »: Conférence donnée le 30 janvier 2009 à l'Ecole Polytechnique par Alain Ferriere (CNRS, Font-Romeu) dans le cadre de séminaire du département Mécanique et de l'Institut Coriolis
  - International Solar Electric technology: http://isetinc.com/
  - Photovoltaic Geographical Information System : http://re.jrc.ec.europa.eu/pvgis/apps3/pvest.php
  - On-line on Air Quality Meteorology: http://www.shodor.org/metweb/index.html